How Atomic Physics Affects Science and Technology

Scenario

Atomic physics has enormously influenced the development of modern science and technology. Advances in atomic physics have profoundly changed scientists' understanding of chemistry, biology, and medicine. A century ago, technology that is taken for granted now would have seemed impossible even in principle. In this project, you will work with two or three classmates to research how the concepts presented in this unit affected an aspect of science or technology.

Planning

Brainstorm with your classmates to make a list of possible topics. Look for branches of science or technology that apply concepts of atomic physics. Here are some starting points:

- medical diagnostic technologies, such as X rays, magnetic resonance imaging (MRI), PET scans, and radioactive tracers
- chemistry applications, such as understanding molecular bonds and using spectroscopy to identify compounds
- biology topics such as quantum effects in photosynthesis and DNA replication
- computer and electronic devices, such as microchips, tunnel diodes, and quantum computers
- nanotechnologies such as nanotubes and atomic force microscopes
- power technologies, such as nuclear reactors, tokamaks, and radioisotope thermoelectric generators (RTGs)

Decide upon a topic to research. Often, you will find it easier to deal with a specific topic rather than a general one. For example, you could focus on nanotubes rather than trying to cover the whole field of nanotechnology. You may want to do some preliminary research on two or three promising ideas to see how much information is available.

Consider the best way to present your findings. You might use a written report, an oral presentation, slides, a poster, a model, a video, or a combination of methods. Consult with your teacher on the format of your presentation.

Assessing Results

Assess the success of your project based on a rubric* designed in class that considers:

- research strategies
- clarity and thoroughness of the written report
- effectiveness of the team's presentation

Materials

- library resources, including books and periodicals
- Web browser and Internet connection

Check with your teacher about any special resources, such as computer software, that you may need for your presentation.

Procedure

1. Assign tasks for each group member. Each member should do part of the research as well as some of the preparation for the presentation, such as writing, preparing graphics, or building a model. Clearly identify who is responsible for each part of your project.
2. Once you have gathered basic information about your topic, consider what further research you need to do. For example, you may be able to interview an expert either in person, or by telephone or e-mail. Many university departments have an outreach program that might suggest an expert you could consult.
3. Check whether the presentation method your group has chosen is suitable for the information you have found during your research. Consult with your teacher if you think you need to change to another type of presentation. If you will be making an oral presentation, practise. Having friends and family critique your presentation can often help you find ways to improve it.

Thinking Further

- Atomic physics often seems to be too abstract or theoretical to have any relevance to the "real world." How has your investigation changed your understanding of the relationship between atomic physics and other disciplines?
- Does the influence of atomic physics extend beyond science? Can you find ways in which atomic physics has influenced the arts or philosophy?
- Science fiction often employs ideas from physics. List several science-fiction books, movies, or television series that use some of the concepts in this unit. How accurate is their treatment of atomic physics?

*Note: Your instructor will assess the project using a similar assessment rubric.

UNIT VIII SUMMARY

Unit Concepts and Skills: Quick Reference

Concepts	Summary	Resources and Skill Building
Chapter 15	**Electric force and energy quantization determine atomic structure.**	
	15.1 The Discovery of the Electron	
cathode rays	Thomson's experiments showed that cathode rays are subatomic particles with a negative charge.	15-1 QuickLab
charge-to-mass ratio	You can use electric and magnetic fields to measure the charge-to-mass ratio of a particle.	Example 15.2
	15.2 Quantization of Charge	
charge quantization	Electric charge exists only in multiples of the fundamental unit of charge, e.	15-2 QuickLab
Millikan's experiment	Millikan's oil-drop experiment measured the charge on an electron and showed that charge is quantized.	Example 15.3 eSIM of Millikan's oil-drop experiment
	15.3 The Discovery of the Nucleus	
classical model of the atom	Rutherford's gold-foil experiment led to the solar-system model with electrons orbiting a tiny positively charged nucleus at the centre of the atom.	15-3 QuickLab Example 15.5
	15.4 The Bohr Model of the Atom	
spectra	Elements and compounds have characteristic emission and absorption line spectra.	15-4 Design a Lab
Bohr model	The Bohr model uses energy levels to account for stability of the atom and to explain line spectra. This model accurately predicts many properties of hydrogen, but has several serious failings.	Example 15.6
energy levels	An electron in an atom can occupy only orbits that give the electron discrete, quantized amounts of energy that are inversely proportional to the square of the principal quantum number.	Example 15.7 15-5 Inquiry Lab
	15.5 The Quantum Model of the Atom	
quantum mechanical model	The wave properties of electrons lead to a powerful new model based on probability distributions.	Figures 15.24–15.25
Chapter 16	**Nuclear reactions are among the most powerful energy sources in nature.**	
	16.1 The Nucleus	
nuclear structure	Nuclei contain protons and neutrons bound together by the strong nuclear force.	Examples 16.1 and 16.2
mass-energy equivalence	Mass and energy are equivalent, and the one can be transformed into the other.	Example 16.3
binding energy, mass defect	The binding energy and mass defect of a nucleus indicate how tightly its nucleons are bound together.	Figure 16.3 Example 16.4
	16.2 Radioactive Decay	
nuclear decay, transmutation	Some nuclei spontaneously transmute into a different element by emitting an alpha or beta particle. Nuclei can also give off gamma rays. All three types of radiation can be harmful.	Examples 16.5–16.10 16-1 Inquiry Lab 16-2 Design a Lab
	16.3 Radioactive Decay Rates	
half-life, activity	You can use the decay constant and the half-life of a radioisotope to predict the activity of a sample.	Examples 16.12 and 16.13
	16.4 Fission and Fusion	
nuclear reactions	Both the fission of a heavy nucleus into smaller nuclei and the fusion of light nuclei into a single heavier nucleus can release tremendous amounts of energy.	Figures 16.17 and 16.18 Examples 16.14–16.16
Chapter 17	**The development of models of the structure of matter is ongoing.**	
	17.1 Detecting and Measuring Subatomic Particles	
particle tracks	The existence and basic properties of subatomic particles can be determined by analyzing the paths of particles in magnetic and electric fields.	Example 17.1 17-1 QuickLab, 17-2 Inquiry Lab
	17.2 Quantum Theory and the Discovery of New Particles	
antimatter	Quantum theory predicted the existence of antimatter, which was confirmed by Anderson's discovery of the positron.	Figure 17.11
quantum field theory	According to this theory, the electromagnetic and nuclear forces are mediated by virtual particles.	Figure 17.13
	17.3 Probing the Structure of Matter	
particle accelerators	Particle accelerators produce high-energy particles, which are used to study the structure of matter.	Figure 17.14
families of particles	Hadrons interact via the strong nuclear force, whereas leptons do not. Bosons have integer spin and fermions have half-integer spin.	Tables 17.2 and 17.3
	17.4 Quarks and the Standard Model	
fundamental particles	The fundamental particles are the six leptons, the six quarks, and their antiparticles. All hadrons consist of a combination of quarks and/or antiquarks.	Tables 17.5,17.6, and 17.7

Vocabulary

1. Using your own words, define these terms:

absorption line spectrum
activity (A) or decay rate
alpha radiation
antimatter
atomic mass number
atomic mass unit (u)
atomic number
baryon
becquerel (Bq)
beta (β) particle
beta radiation
beta-negative (β^-) decay
beta-positive (β^+) decay
binding energy
Bohr radius
boson
bubble chamber
cathode ray
cloud chamber
colour
cyclotron
daughter element
decay constant
drift tube accelerator
electroweak force
elementary unit of charge
emission line spectrum
energy level
excited state
femto
fermion
fission
Fraunhofer line
fundamental particle
fusion
gamma (γ) decay
gamma radiation
gluon
grand unified theory
graviton
gray (Gy)
ground state
hadron
half-life
ionization energy
isotope
lepton
mass defect
mediating particle
meson
muon
neutrino
neutron
neutron number
nucleon
nucleosynthesis
orbital
parent element
pion
planetary model
positron (e^+ or ${}^0_1\beta$)
primary cosmic rays
principal quantum number
proton
proton-proton chain
quantum chromodynamics
quantum electrodynamics
quantum field theory
quark
radioactive decay series
radioisotope
relative biological effectiveness (RBE)
secondary cosmic rays
sievert (Sv)
spectrometer
spectroscopy
spin
standard model
stationary state
strange particle
string theory
strong nuclear force
supernova
synchrotron
transmute
Van de Graaff accelerator
virtual particle
weak nuclear force

Knowledge

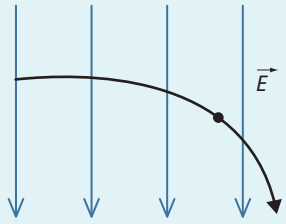
CHAPTER 15

2. Calculate the electrical charge carried by 1 kg of protons.

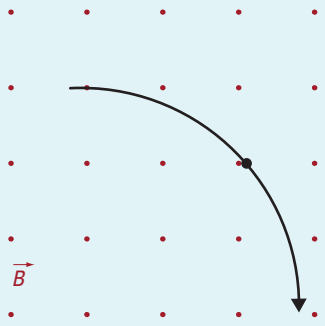
3. How many coulombs of charge are on a dust particle that has gained 10 electrons?

4. Calculate the force exerted by an electric field of strength 100 N/C [S] on a dust particle having a charge of $-10e$.

5. Explain how the path of this particle shows whether its charge is positive or negative.



6. Determine whether the charge on this particle is positive or negative.



7. What is an alpha particle?

8. Here are four energy-level transitions for an electron in a hydrogen atom:

$n_i = 1 \rightarrow n_f = 5$ $\quad$ $n_i = 4 \rightarrow n_f = 1$

$n_i = 2 \rightarrow n_f = 6$ $\quad$ $n_i = 6 \rightarrow n_f = 2$

(a) For which transition(s) does the atom lose energy?

(b) For which transition does the atom gain the most energy?

(c) Which transition emits the shortest wavelength photon?

9. You are comparing the energy released by two different atomic transitions in a mercury atom. Transition A produces a very bright green line while transition B produces a fainter violet-coloured line. Which of these transitions releases more energy? Explain.

CHAPTER 16

10. How many neutrons are in a nucleus of gallium $^{64}_{31}$Ga? How many protons?

11. Why is the mass of an atom always less than $Zm_{^1_1\mathrm{H}} + Nm_{\mathrm{neutron}}$?

12. Express the energy equivalent of 0.021 u of mass in electron volts.

13. Express the energy equivalent of 7.0 u in joules.

14. Calculate the binding energy for a nucleus that has a mass defect of 0.0072 u.

15. What is the activity of a sample that contains 1.5×10^{22} nuclei of an element with a decay rate of 1.5×10^{-13} Bq?

16. Write the β^+ decay process for $^{18}_{9}$F, and identify the daughter element.

17. The half-life of sulfur-35 is 87.51 days. How much of a 25-g sample of this isotope will be left after a year?

18. Write the alpha decay process for $^{228}_{90}$Th and identify the daughter element.

19. Explain the difference between fission and fusion.

CHAPTER 17

20. What is a positron?

21. What is a pion?

22. If an electron and positron collide, they annihilate each other and are converted into energy.

(a) How much energy does the annihilation of a positron-electron pair produce?

(b) Explain why the annihilation must produce two gamma rays with the same wavelength.

(c) Estimate the wavelength of these gamma rays. Assume that the kinetic energy of the electron and positron was negligible.

23. What is a quark?

24. Describe this reaction in words:
$\bar{\nu}_e + p \rightarrow n + e$

25. Identify the particle formed by each of these combinations of quarks:

(a) uud $\quad$ (b) $u\bar{s}$

(c) $u\bar{d}$ $\quad$ (d) dds

26. Use quarks to describe how a neutron decays into a proton and an electron.

Applications

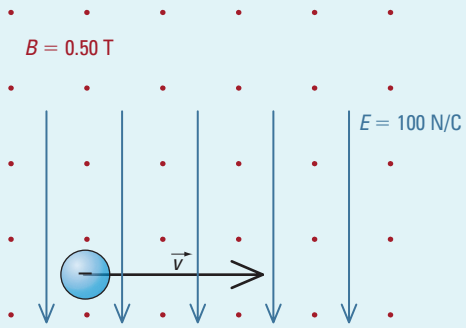
27. A beam of protons enters a vacuum chamber where the electric field strength is 400 N/C and the magnetic field strength is 0.550 T.

(a) Sketch an orientation of the electric and magnetic fields that could let the protons pass undeflected through the chamber.

(b) What speed must the protons have if they are not deflected by this orientation of the fields?

28. Find the magnetic field strength that will deflect a sodium ion (Na^+) in an arc of radius 0.50 m when the ion has a speed of 1.0×10^6 m/s.

29. This diagram shows an electron moving at 2.5×10^6 m/s through perpendicular electric and magnetic fields.



(a) Calculate the electric and magnetic forces acting on the electron.

(b) Calculate the net force acting on the particle.

30. An oil droplet with a mass of 1.6×10^{-16} kg is suspended motionless in a uniform electric field of strength 981 N/C [down].

(a) Find the charge on this droplet.

(b) How many electrons has the droplet either gained or lost?

31. (a) Find the wavelengths of the first four spectral lines produced by transitions into the $n = 3$ energy level of a hydrogen atom.

(b) What part of the electromagnetic spectrum are these lines in?

32. (a) Use the Bohr model to calculate the radius of the $n = 2$ energy level in a hydrogen atom.

(b) Find the de Broglie wavelength for an electron in this energy level.

(c) Use the formula for the de Broglie wavelength to find the momentum of this electron.

(d) Find the electron's speed and kinetic energy.

33. Calculate the binding energy for ${}^{40}_{20}\text{Ca}$.

34. Identify the nucleus produced in each reaction.

(a) ${}^{12}_{6}\text{C} + \gamma \rightarrow ? + \alpha$

(b) ${}^{14}_{7}\text{N} + \alpha \rightarrow ? + \text{n}$

(c) ${}^{206}_{81}\text{Tl} \rightarrow ? + \beta^- + \bar{\nu}$

35. Explain why each of these reactions cannot occur.

(a) ${}^{15}_{6}\text{C} \rightarrow {}^{15}_{5}\text{B} + \beta^+ + \bar{\nu}_e$

(b) ${}^{3}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + \beta^+ + \nu_e$

(c) ${}^{23}_{11}\text{Na} + \text{n} \rightarrow {}^{19}_{9}\text{F} + \alpha$

36. How much energy is released by β^- decay of ${}^{16}_{7}\text{N}$?

37. Some blood-flow tests use iodine-131 as a tracer. This isotope has a half-life of 8.04 days. Estimate the percentage of iodine-131 left after 30 days.

38. How much energy is given off in the alpha decay of neodymium isotope ${}^{144}_{60}\text{Nd}$? What daughter element does this decay produce?

39. A radioactive sample has an activity of 0.50 MBq and a half-life of 6 h. What will the activity of the sample be after 3.0 days?

40. The proportion of carbon-14 in charcoal used in a cave painting is only 12.5% of the proportion in living trees nearby. Estimate the age of this cave painting.

41. Calculate the amount of energy released when a carbon-12 nucleus absorbs an alpha particle and transmutes into oxygen-16.

42. Calculate the energy released by the reaction ${}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{1}\text{H} + \text{p}$.

43. (a) What fundamental particles does a neutron contain, according to the standard model?

(b) Show that this combination of particles has zero net charge.

44. The size of a nucleus is in the order of 1 fm.

(a) Calculate the electrostatic force of repulsion between two protons separated by 1 fm.

(b) Determine the potential energy of this pair of protons.

(c) What keeps a nucleus together despite the electrostatic repulsion between protons?

Extensions

45. Two hydrogen atoms in the ground state collide head on and both ionize. Find the minimum speed at which the atoms could have been moving toward each other.

46. (a) Describe the reaction $\gamma + \text{p} \rightarrow \pi^0 + \text{p}$ in words.

(b) Calculate the minimum energy the photon must have to produce this reaction.

47. In β^+ decay, a proton becomes a neutron and the nucleus emits a positron and a neutrino. A proton has less mass than a neutron, and the positron and the neutrino carry away some mass and energy. Explain how such decays conserve mass-energy despite this apparent imbalance.

48. A 5.0-GeV photon creates, via pair-production, an electron and a positron. Calculate the total momentum of the two particles and sketch their motion relative to the path of the original photon.

49. Imagine that protons and electrons were not charged but could still form a hydrogen atom through gravitational attraction. Calculate the size of such an atom by finding the radius of the ground state. (Hint: Assume that the electron travels in a circular orbit and has a total energy of $-\frac{Gm_\text{p}m_\text{e}}{2r}$.)

50. A typical banana contains about 0.40 g of potassium. Naturally occurring potassium is mainly ${}^{39}_{19}\text{K}$, but 0.012% of it is the radioactive isotope ${}^{40}_{19}\text{K}$, which has a decay constant of $1.8 \times 10^{-17}\ \text{s}^{-1}$. The average atomic mass for natural potassium is 39.1 u.

(a) Calculate the activity of a typical banana.

(b) Does the radiation exposure from bananas outweigh their health benefit as a source of potassium, fibre, and vitamins A, B6, and C? Explain your reasoning.

51. A spill of radioactive material at an industrial site emits 1.25 mGy per hour, measured at a distance of 1.0 m from the spill. The relative biological effectiveness of this radiation is 2.

(a) Compare the radiation dose from this spill to exposure from background radiation.

(b) At what distance from the spill would the annual absorbed dose be less than 0.1 mSv?

(c) A newspaper headline reads "Dangerous Spill at Local Factory." Is this description fair? Explain why or why not.

52. (a) What is the fundamental difference between a fusion process and one that combines matter and antimatter?

(b) Compare the energy released by the fusion of ordinary hydrogen into helium-4 with the energy released by combining two protons with two antiprotons.

(c) Why can antimatter not be used for generating power or propelling a spaceship now?

53. Suppose that an electricity generator powered by the fusion reaction ${}^{2}_{1}\text{H} + {}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n}$ has an overall efficiency of 20%. How much deuterium and tritium will this generator need to produce 10 MW·h of electricity, the annual consumption of a typical home?

Skills Practice

54. After two years, 6% remains of the original radioisotope in a sample. Estimate the half-life of this isotope.

55. A nucleus of boron ${}^{10}_{5}\text{B}$ absorbs an alpha particle and emits a proton. Use nuclear notation to write this reaction process, and identify the element that it produces.

56. Does an electron that moves from an energy level of -5.1 eV to an energy level of -6.7 eV emit or absorb a photon? Find the wavelength of the photon.

57. How much energy is produced by the conversion of 0.250 u of matter into energy?

58. Calculate the radius of a hydrogen atom in the $n = 2$ state.

59. An electron jumping from the $n = 3$ to the $n = 2$ state in a hydrogen atom emits a 656-nm photon.
(a) Which state has the greater energy?
(b) Find the energy difference between the two states.

60. Calculate the binding energy for $^{24}_{12}\text{Mg}$.

61. Find the parent atom for this decay:
$? \rightarrow {}^{14}_{7}\text{N} + e^- + \overline{\nu}$

62. Calculate the electrical charge of a particle composed of the quarks uus.

63. Find the activity of a sample containing 1.5×10^{20} radioactive atoms with a decay constant of $3.5 \times 10^{-15}\ s^{-1}$.

Self-assessment

64. Outline how you would describe Rutherford's gold-foil experiment to a friend. Explain why the results were startling for physicists in 1910.

65. (a) Explain why classical physics predicts that hydrogen will always produce a continuous spectrum rather than discrete spectral lines.
(b) How does the Bohr model explain spectral lines?

66. Draw a concept map of the atomic physics topics that you find the most difficult. If you have trouble completing this concept map, discuss the concepts with a classmate or your teacher.

67. Explain why pair annihilation, such as $e + e^+ \rightarrow 2\gamma$, does not violate the law of conservation of mass.

68. List the four fundamental forces and explain which ones are involved in nuclear binding energy, decays, fission, and fusion.

eTEST

To check your understanding of atomic physics, follow the eTEST links at www.pearsoned.ca/school/physicssource.